ture on the absorption spectrum will not be so great as at the lower pressure of the emission layer. We may assume curve (c) of figure 4 to represent with sufficient accuracy the radiation coming to the surface from a cold atmosphere, but not the radiation leaving the atmosphere at high levels. From observations of polar continental air at low temperatures, it becomes possible to place an upper limit on the amount of radiation that leaves the atmosphere by way of the emission layer. A surface temperature of −60° C., which has commonly been observed in Alaska and Siberia, corresponds to an equilibrium temperature of −34° C. for the isothermal layer above it.[11] From the difference between curves (a) and (c) of figure 4, the net loss of radiation to space from the surface is found to be 0.054 gm cal/cm^2/min. The loss to space from the emission layer must not exceed this amount, for otherwise the atmosphere could not cool and at the same time preserve a stable lapse rate in lower levels. An even lower limit can be placed on the radiation if we notice that the isothermal layer in sounding (a), figure 1, of the writer's previous paper, has a temperature of −41° C., corresponding to an equilibrium surface temperature of −66° C. In this case the net loss of radiation from the surface is 0.044 gm cal/cm^2/min., which is an upper limit to the loss of radiation from the emission layer.

In conclusion, it therefore appears that model B is more satisfactory for computations which involve atmospheric radiation than is model A. Furthermore, the measurements of Weber and Randall, and the effects of low temperature and pressure on absorption, together indicate that the atmosphere is more transparent to long-wave radiation than formerly thought; and this is verified by our knowledge about the structure and rate of cooling of polar continental air. However, further laboratory measurements or theoretical determinations of the absorption constants of long wave radiation by water vapor and carbon dioxide at low temperatures and pressures are much needed.

AIRCRAFT ICING ZONES ON THE OAKLAND-CHEYENNE AIRWAY

By John A. Riley

[Weather Bureau, Oakland Calif., February, 1937]

The formation of ice on aircraft is one of the greatest hazards to air traffic today, with the accompanying complications of turbulence which makes the airplane difficult to control and of static which interferes with the operation of vocal and directional radio facilities. The meteorological aspect of the problem has been somewhat simplified in recent years by the recognition that most icing, (as well as other unfavorable conditions, such as precipitation, low ceiling, and poor visibility) occurs in restricted areas: First, along the moving fronts that separate different air masses; and second along high mountain ranges. The worst conditions in the far West occur when the two coincide, that is, while a front is passing over a mountain range.

The icing zones along mountain ranges will be considered first. During the winter, strong westerly winds blowing across mountain ranges cause severe turbulence along the crest of the mountains where the air flow is greatly accelerated. Along the Oakland to Cheyenne route there are four ranges over 8,000 feet high: Sierra Nevada, Ruby, Wasatch, and Rocky Mountains. During cloudy, rainy weather over the coastal region and Pacific slope, snows in the intermountain region, and westerly gales with near freezing temperatures along the mountain crests, a zone of severe icing occurs in the region of turbulence along the top of these high ranges.

Before it was known that severe icing is to be expected in the turbulent region along a mountain crest, the pilot would frequently push into it and, upon starting to take on ice, would turn back and climb higher, repeating the process if necessary until he was above it or returning to the point of departure. Due to a better understanding of the condition, such procedure is no longer necessary; instead the pilot climbs above the icing zone before reaching the mountains, generally 12,000 feet or slightly higher, and maintains this altitude until safely beyond the icing zone on the other side. (See figure 1.)

While he is climbing through clouds, and possibly through light precipitation over the valleys, a slight amount of ice forms as the airplane climbs through a stratum having temperatures ranging from freezing to 25° F. or lower, but in the absence of turbulence the deposit is not likely to be serious; after reaching smooth air at higher altitudes with a temperature of 18° to 20° F., the density of clouds in the West is so reduced that flight can be continued without the formation of a dangerous amount of ice. Pilots report that stratified clouds at high levels are sometimes so tenuous that the outline of convective type clouds penetrating them can be seen; icing and static begin immediately if the convectional cloud formation is entered.

Icing zones have been observed along all the high ranges of the West; they occur whenever strong winds carry clouds and precipitation across them in winter. The Sierra Nevada Range is an outstanding example because of its length and height and because the air flowing over it is characterized by high temperature and humidity. Experimental trips have shown the presence of heavy ice in the updraft along the western slope of the high coastal ranges in southern California. *Severe* icing over the mountains of northern California and southern Oregon is generally associated with fronts rather than the updrafts caused by the mountains, since the route is shielded somewhat from such updrafts by higher mountains west of the airway.

Pilots on the Salt Lake-Cheyenne division have found an icing zone over the Wasatch Mountains similar to that over the Sierra Nevada. A pilot reports that "A cloud bank will build up on the western slope of the range causing over-the-top or instrument flying into Salt Lake City from the east, with broken clouds west of the lake and east of Coalville or Knight. Often the area is more extensive, as the clouds bank up on the Uintas to the south of Knight, necessitating an instrument flight of 30 to 50 minutes" (fig. 2). Another states: "I know of no cases of severe icing being found over the Wasatch while flying above 12,000 feet and with temperatures below 20° F. I have also noted that almost without exception the amount of icing and the turbulence increases several fold during the few minutes we are directly above the highest peaks."

Another pilot, however, has reported rapid accumulation of ice while flying in a cloud at 14,000 feet over the Wasatch Mountains with temperature between zero and

[11] H. Wexler, Cooling in the Lower Atmosphere and the Structure of Polar Continental Air, Monthly Weather Review, 64, 122, April 1936.

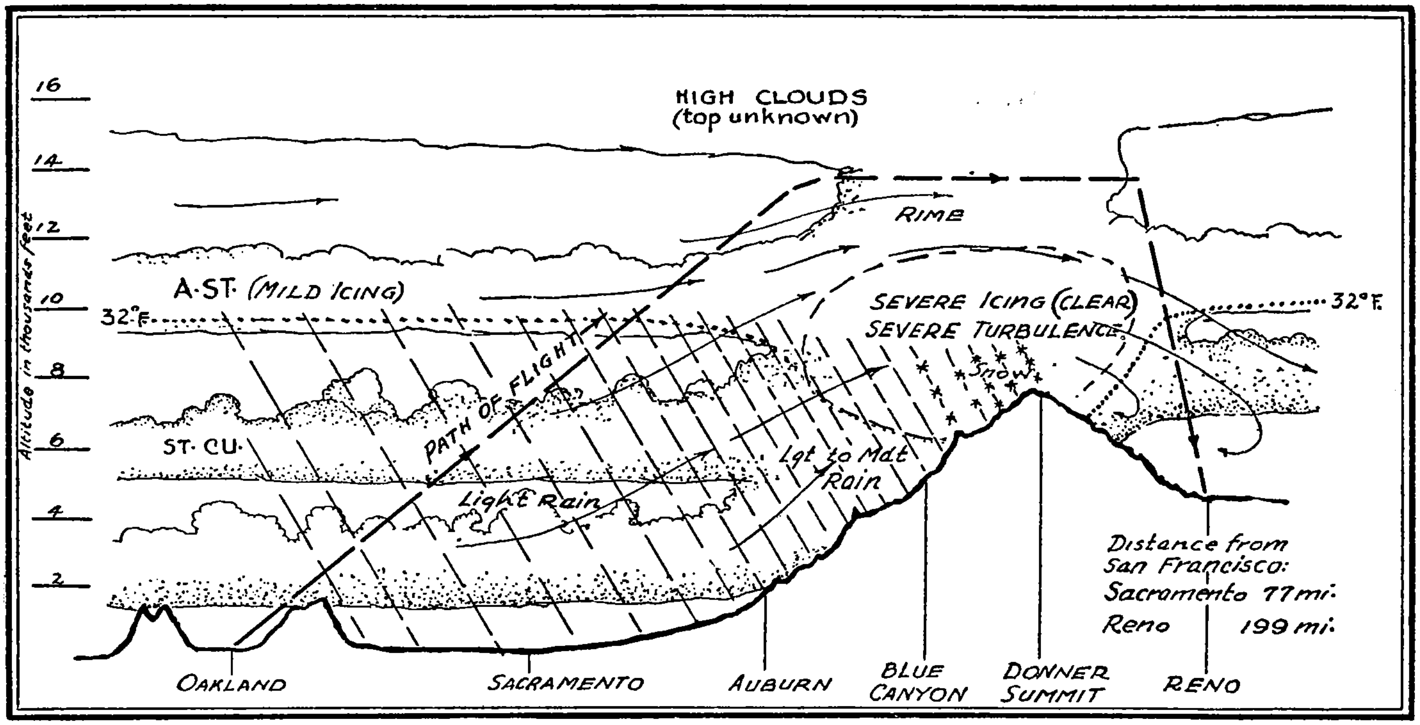

FIGURE 1.—Vertical cross section along the San Francisco airway, showing region of severe icing and the flight path to avoid icing.

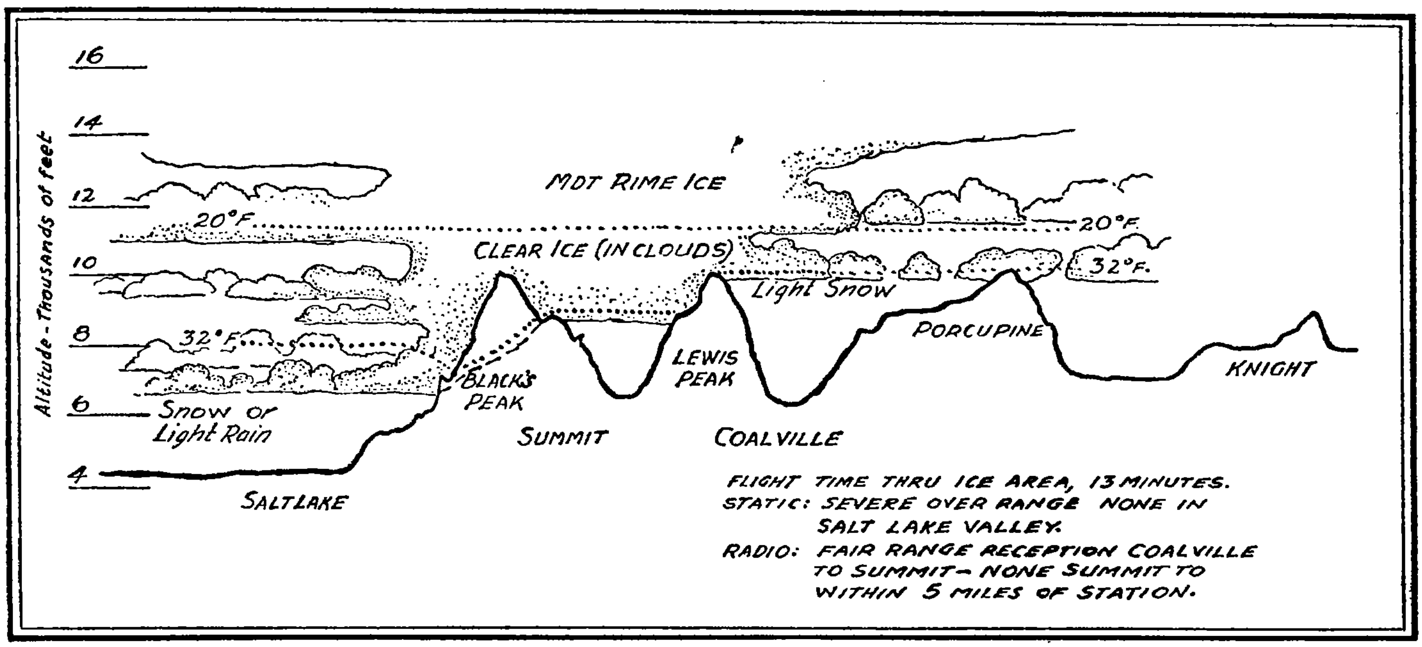

FIGURE 2.

10° F., the airplane taking on a heavy coating of ice within 10 minutes. The circumstances of this flight are not known, but the icing was probably within a front; a somewhat similar experience is cited in the section on icing along fronts in this paper.

From Pendleton comes the statement: "We have a condition here in the Northwest that closely parallels that over the Sierras. To the east are the Blue Mountains and to the west the Cascade Range. Icing is quite prevalent for planes passing through either area, especially over the Blue Mountains because the temperatures are generally lower and it is often necessary to climb to 18,000 to 20,000 to get on top of all cloud formations."

FORECASTS

The surface weather map, wind-aloft charts, and aerographic flights all contribute data of fundamental importance in the preparation of airway forecasts. Pilots keep a log of all trips, based on observations at 30-minute intervals; along the west slope of the Sierra Nevada temperature readings are made for every thousand feet. Along an airway where several trips are made daily, a good cross section is obtainable. Frequent temperature readings show that when icing conditions exist, the saturation adiabatic lapse rate prevails from near the surface to 13,000 feet.

There are times, however, when neither pilots' logs nor aerographic soundings are available and the structure of the air streams must be determined from surface data. Over the Sierra Nevada, the surface observations at Blue Canyon (5,300 feet) and Donner Summit (7,200 feet) are closely representative of the free air during periods having strong winds. Mountain stations nearer the coast furnish information of the greatest value: Mount Wilson, Sandberg, Mount Hamilton, Mount Shasta, Siskiyou Summit, and Sexton Summit, all above 4,000 feet, form an elevated frontier from southern California to southern Oregon.

The regular airway forecasts are supplemented, upon request, by trip forecasts. A picture of the weather conditions in which many flights have been completed between Reno and the coast may be obtained from one of these forecasts, such as that for January 10, 1936:

Overcast to broken clouds in the Bay region, with ceiling 1,000 to 3,000 feet and visibility 10 miles or more except zero along the hills; overcast with light rain, low ceiling and visibility in the Sacramento Valley and lower west slope of Sierra, and light to moderate snow with ceiling and visibility zero over high Sierra. High and lower broken clouds at Reno with ceiling 1,500 to 3,500 feet and visibility 6 to 15 miles. Wind WSW. 55 to 65 m. p. h. 8,000 to 11,000 feet, becoming west to WNW. and decreasing somewhat in speed above 12,000. Moderate to severe icing 8,000 to 11,000 over summit and high west slope of Sierra.

ICE

Classification.—Two forms of icing occur under different conditions, clear ice and rime. Clear ice forms at the higher temperatures, 32° to about 23° usually; when raindrops and large subcooled cloud particles strike the plane and spread, a tenacious covering difficult to break loose is formed. Clear ice sometimes builds up rapidly on the leading edge of the wing. On account of the temperatures at which it forms, clear ice usually occurs at elevations below 10,000 feet.

Rime consists of hard whitish ice, formed by small water particles which crystallize as they strike, forming a coarse granular structure, which is more easily removed by the wind and vibration than clear ice. Rime occurs with temperatures of 20° F. or lower and at elevations above 10,000 feet as a rule: (1) (2) (3) (7).

In the turbulent area over mountain crests, the ice formation is usually a mixture composed of rain drops, snow, and sometimes sleet, which builds into irregular surfaces that greatly disturb airflow and reduce the speed of the airplane.

Protection.—Methods of protection from ice now in use include rubber de-icers on the leading edge of the wing, alternately inflated and deflated to break up the ice; and "slinger rings" which spread a film of alcohol and glycerine to the propellor blades that, if turned on before icing starts, causes the ice to slip from the propellors as it forms and thus prevents serious vibration.

The practice, initiated several years ago, of heating the carburetor intake almost eliminates a once common icing hazard.

ICING ALONG FRONTS

The predominating characteristics of the weather map have been different for each of the past three winters. During the winter of 1934–35, with low pressure areas moving southeastward from Canada into the interior of the United States, a procession of cold fronts extending NE–SW moved southeastward across the western highlands, losing little of their intensity and carrying moderate to heavy snow and very low ceilings eastward to the Rockies.

During the winter of 1935–36, a series of storms moved eastward across the Pacific some 10° south of the usual course, forced southward by an Arctic ring of high pressure. At the time that these storms were entering northern California or Oregon, upper air charts show that the surface high pressure area in Canada was surmounted by a low pressure area in the upper levels with a pronounced pressure gradient from south to north and strong westerly winds.

With the extensive flow of air eastward across the Pacific, a series of weak fronts separating modified polar Pacific (NPP) and modified tropical Pacific (NTP) air masses swept across the western part of the country causing almost continuous overcast and snow and fog in the mountains; the heaviest precipitation occurred and the fronts were most severe in the Sierra Nevada, Cascade, and higher coast ranges; they lost some of their intensity farther east with loss of moisture and decreasing lapse rate.

During the winter of 1936–37 another type has predominated. With intense high pressure over Alaska and another high in the Pacific north of the Hawaiian Islands, a region of frontogenesis has prevailed in the northeast Pacific. As these storms have developed and moved southward off the coast, pushed southward by a very extensive flow of Pc air from the interior of the North American continent westward into the Pacific, heavy precipitation has resulted in the West. Reed has called this the "easterly type"; it gives the Pacific slope south of Cape Mendocino the wettest, stormiest weather to which it is ever subjected (4).

As these storms have moved inland with the usual warm and cold front phenomena, the most interesting feature has been the upper cold front, that is, a flow of cold air in the upper levels across the surface disturbance along the coast. The cold air is carried forward by the stronger winds aloft, and the passing of the front is marked by rising pressure and improving ceiling and visibility.

With a clear concept of the upper cold front, comes a better understanding of the disintegration of the LOWS along the coast and their regeneration beyond the Sierra Nevada Mountains. After reaching the interior highlands, the upper cold front may either dissipate or become a surface cold front with the redevelopment of the LOW and the warm front precipitation in the forward sector.

The severity of icing along either a warm or cold front depends on the intensity of precipitation which in turn can be judged to some extent by the steepness of the pressure gradient.

Warm fronts.—When icing in overrunning warm air is more severe where the heavier precipitation is taking place along the warm front, this fact indicates that the frontal surface is steep and therefore that it can be passed through in a shorter time. In most cases, severe icing in the overrunning air along a warm front can usually be escaped by a change in altitude of 1,000 to 2,000 feet, provided the pilot keeps in mind the direction of slope of the frontal surface. Normally, the temperatures in the lower air are too high for ice formation.

Many flights are successfully completed by flying in the inversion above an icing condition but it is important to remember, that it is not always possible to find temperatures above freezing over a region of freezing mist, as Kaster has pointed out (5): "The experiences of commercial pilots have shown that after cloud particles become subcooled, further condensation can take place causing the subcooled particles to grow until they fall as mist or even light rain. Under these conditions freezing mist may be found from the ground up to the cloud base,

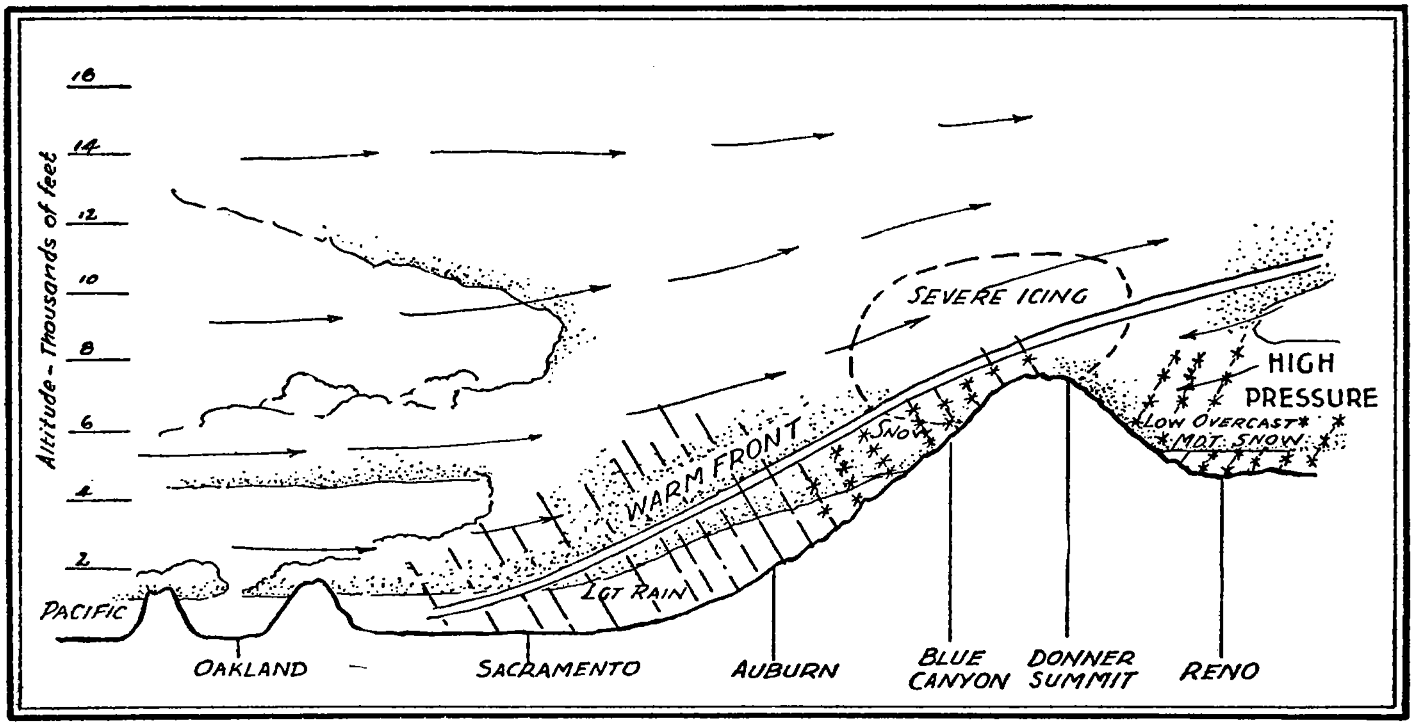

FIGURE 3.

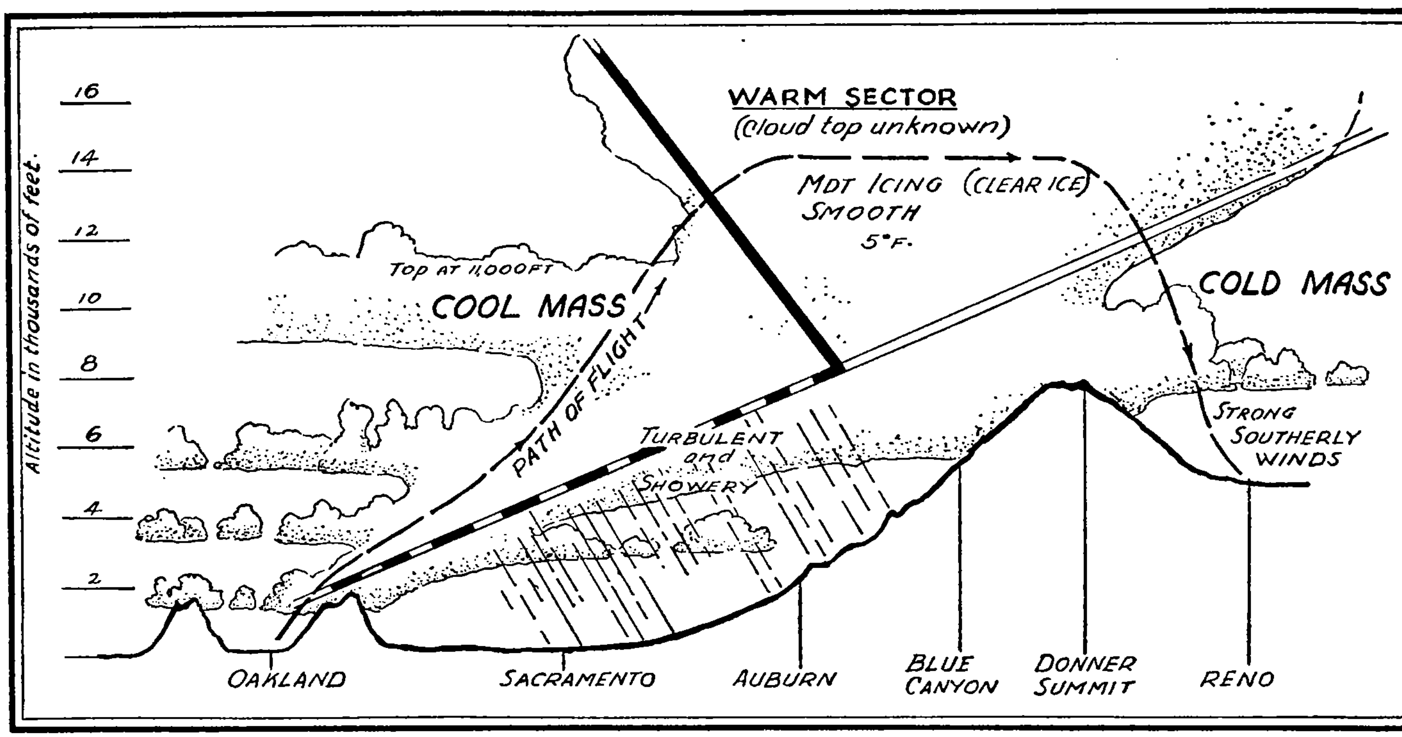

FIGURE 4.

and subcooled cloud particles from there to the top of the cloud." This condition has been frequently observed in the East.

Pilots on the midcontinent airway seldom encounter severe icing in warm fronts between San Francisco and Salt Lake City, except while the front is passing over the mountains. An exception to this is a warm front which approaches the mountains when high pressure is built up along the east side; in this case the high pressure is in effect a continuation of the upward slope of the mountains, and the warm front is continuous and active to great heights (fig. 3). But it is generally observed that the turbulent descent of the air along the eastern slope tends to break up the front to such an extent that conditions are not favorable for heavy icing (fig. 1). The surface of discontinuity again forms as the warm air overruns the next range, but always with decreased intensity after having passed higher ranges to the west.

On the night of January 27, 1937, an eastbound pilot took on ice rapidly for a few minutes over the Sierra Nevada summit in smooth air at 14,000 feet, where the temperature was 5° F., while a small lapse rate prevailed from the 10,000-foot level. Rapid icing under these conditions is unusual; examination shows that he had passed through the complicated frontal structure shown in figure 4. Near the coast the weather was showery and the air turbulent; over the Sacramento Valley the pilot came out on top at 11,000 feet, but soon flew into an overcast again and continued on instruments until over Reno. The wedge of cold air was lifting a large amount of moisture in the warm sector, and it was while flying through this warm sector that the ice formed. The ice so formed was composed of three layers of clear ice separated by crystallized layers; and according to the pilot the ice was "as tough as glue" when he reached Reno.

Cold fronts.—Cold-front surfaces vary greatly in vertical extent and violence; many of the cold fronts of the West are rather weak because they separate air masses that have had a long journey over the Pacific and have become considerably modified. The humidity, both relative and specific, is high but the temperature contrasts are not marked.

Fronts caused by an outbreak of fresh Pc or Pp air should generally be avoided. In any cold front, moderate to severe icing is to be expected for a short time if there is vigorous turbulence and if the temperatures are below freezing. Further, icing is possible in a cold front at heights of 18,000 to 20,000 feet and temperatures below zero Fahrenheit.

An important factor to be kept in mind by the pilot is the direction of the front relative to his course; if it is perpendicular to the course, he should be able to fly through it in a few minutes, but if it is parallel to the course he might have to remain within the active frontal zone a long time and take on a heavy coating of ice.

Cold-air mass clouds.—Pilots have sometimes picked up a heavy coating of ice in a few minutes while passing through detached cumulus clouds following a cold front; it is always advisable to avoid cumulus tops when temperatures are below freezing because of the large amount of moisture carried upward by the vertical currents within the cloud.

ATTENDANT CIRCUMSTANCES

Static.—Flight through icing zones is almost invariably attended by static, frequently referred to as snow static. In warm-front precipitation static is continuous; in cold fronts static is sporadic and apparently proportional to the strength of convection or turbulence; it therefore varies from one section of a cloud to another, and from one height to another. Strong static sometimes occurs in the detached cumulus clouds of a cold air mass as previously mentioned. Static usually stops at once when (*a*) the airplane leaves the cloud formation or (*b*) the airplane descends into above-freezing temperatures.

Winds.—In their attempts to avoid icing conditions by climbing to high altitudes pilots are aided by the ever-increasing speed of airplanes and their cruising range, but with the possibility of loss of contact with the ground by radio on account of static, it is highly important for the pilot to understand something of the factors governing winds at high elevations.

Actual pressure gradients at 5,000 feet are plotted for a large number of elevated stations in the West; gradients obtained from aerographic flights in the morning are used in connection with the 10,000- and 14,000-foot wind aloft charts. At other periods of the day stream lines on the upper-air charts are of great help in depicting air flow and in bridging the gaps in wind-aloft reports caused by cloudiness.

This zone of icing and turbulence increases in thickness with the strength of the wind, but the top is generally below 12,000 feet. The zone extends horizontally from the crest 20 to 30 miles to windward and half that distance to leeward. Snow, fog, and zero ceilings prevail along the western slope of the mountains; the clouds which occur in several strata over the valleys come together over the mountains and rise to great heights, so that instrument flying is necessary.

The success of winter-flying operations under these conditions depends to a large extent upon the happy circumstance that usually dynamic heating of the air descending the eastern slopes of the higher ranges produces broken cloud layers, with ceiling and visibility favorable for take-off and landing at points in this area.

Aircraft icing seldom occurs below 5,000 or 6,000 feet along the Pacific coast, because of the relatively high temperatures of Pacific air masses usually moving across this area; in fact, the normal winter temperature along the central California coast is above freezing at all levels below 9,500 feet, with an average of 50° F. at 1,000 feet and 40° F. at 6,500 feet.

But even with these relatively high-average winter temperatures along the coast, the freezing line frequently lowers to an elevation of 6,000 to 7,000 feet along the mountains, as a result of the adiabatic cooling of the rising air streams in passing over them.

Before the advent of commercial aviation, the present Chief of the Weather Bureau, W. R. Gregg, discussed clearly the connection between steep latitudinal temperature gradients and unusually strong westerly winds aloft (**6**). However, the experience of pilots in being forced to high altitudes on account of bad weather below, and there caught in a gale which carried them far off course, shows the need of emphasizing this well-known fact. It follows that when extreme cold prevails in the north and relatively high temperatures to the south, the pilot should be on guard against the possibility of being carried off course by the strong winds which are almost certain to be blowing at high elevations.

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